

# Reinforced Concrete Failure Mechanisms

Best Practices in Dam and Levee Safety Risk Analyses

Part E – Concrete Structures

Chapter E-2

Last modified June 2017, Presented July 2018



US Army Corps  
of Engineers®



# Reinforced Concrete Failure Mechanisms

## OUTLINE:

- Types of Structures
  - Spillway Piers
  - Navigation Lock Walls
  - Floodwalls
  - Slabs
  - Buttresses
- Factors influencing strength and stability of reinforced concrete sections
- National code requirements in the context of risk
- Considerations when determining risk analysis failure probabilities based on structural analysis results
- Typical event tree of the progression of failure

# Reinforced Concrete Failure Mechanisms

## OBJECTIVES:

- Get a broad overview of potential failure modes for different kinds of reinforced concrete structures
- Understand the mechanisms that affect reinforced concrete failures
- Understand how to construct an event tree to represent reinforced concrete failures
- Understand how to estimate event probabilities and probability of breach



# Reinforced Concrete Failure Mechanisms

## SUMMARY OF KEY CONCEPTS:

- Reinforced concrete failure mechanisms are generally well understood but there is significant uncertainty under seismic loading due to limited case histories
- Concrete and reinforcement material properties are well understood and can be determined with confidence for dams and floodwalls.
- Type and Duration of Loading is important to understand – consider both static and earthquake loading
- Ductile and Brittle Failure mechanisms
- Seismic reinforcement details have changed dramatically over the past few decades; older concrete hydraulic structures may be more vulnerable to seismic events
- Use w/ caution modern codes when computing capacity of older reinf. conc. structures
- Typical event tree presented for reinforced concrete buttresses and piers





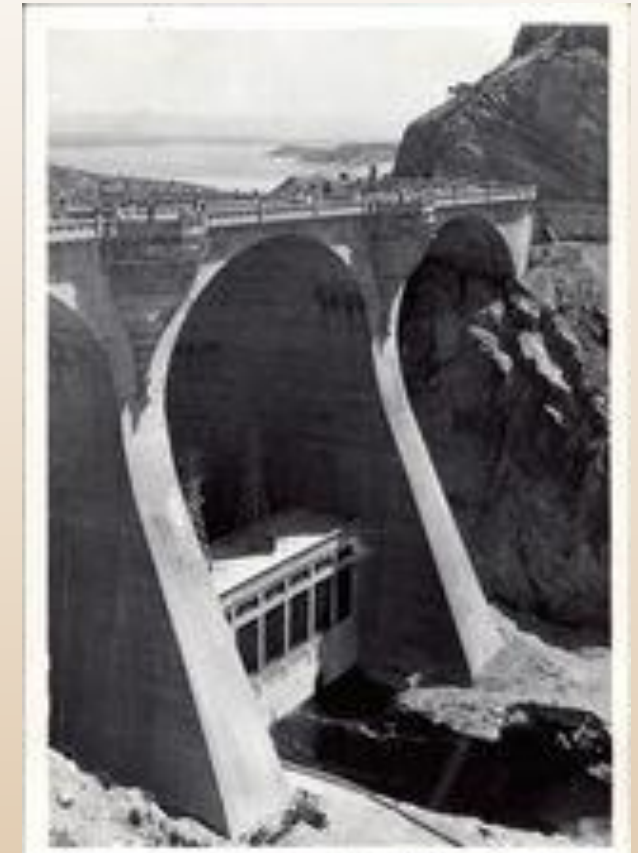
# Geometry and Support Conditions – Piers and Buttresses



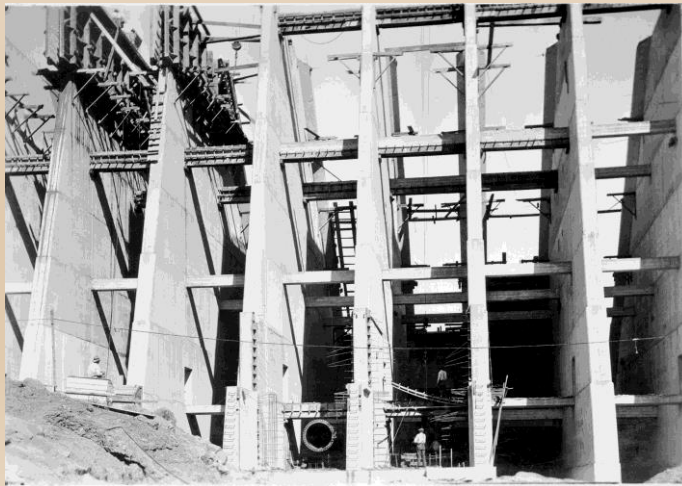
Spillway Gate Piers



Spillway Gate Piers



Thick Buttress Construction



Thin Buttress Construction



# Geometry, Support and Loading Conditions – Floodwalls



Paducah, KY Floodwall:  
2011 Ohio River Flood



New Orleans Floodwall:  
2005 Katrina



Newport, KY Floodwall



Sunbury, PA  
Floodwall: 1972  
Hurricane  
Agnes flood  
loading,  
Susquehanna  
River



Damage to  
Floodwall by an  
Aberrant Barge  
During Hurricane  
Gustav (Orleans  
East Parish)

# Geometry, Support and Loading Conditions – Floodwalls



New Orleans Lower Ninth  
Ward  
Failed I-Wall:  
September 2005  
Hurricane Katrina



# Geometry, Support and Loading Conditions – Floodwalls



New Orleans Floodwall:  
Barges against face of floodwall  
2005 Katrina



St. Bernard Parish, New  
Orleans - Damage to top of I-  
Wall from a Barge:  
2005 Hurricane Katrina



Damage to Floodwall by an  
Aberrant Barge during  
Hurricane Gustav, 2008  
(Orleans East Parish)



# Geometry, Support and Loading Conditions – Navigation Locks & Dams



Tow w/loaded coal barges



Damage from Barge Impact



Belleville L&D Barge Accident,

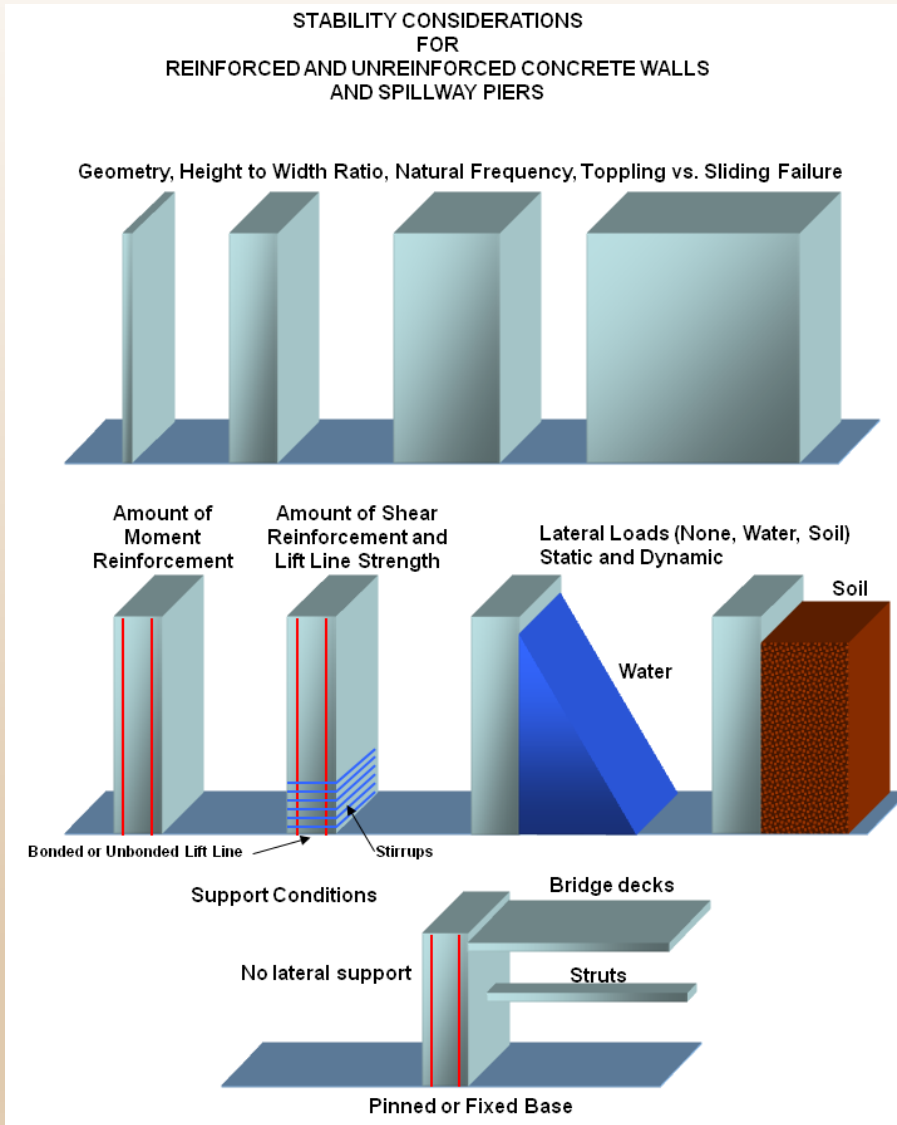
Mississippi  
River Lock  
No. 2  
Barge  
Impact  
Guide Wall



Maxwell Dam,  
Monongahela River,  
November 1985



# Geometry and Support Conditions



- Reinforced concrete sections in hydraulic structures vary greatly in size and shape
  - ✓ Spillway walls and Floodwalls can be very tall and narrow
  - ✓ Spillway piers and floodwall closure abutments tend to be shorter and wider than walls
  - ✓ Buttresses can vary from very thin tall sections to more stout sections
- The geometry of the concrete section can have a significant impact on how the section fails
- Sections with height to width ratios of 4:1 or less tend to slide more than rotate or bend while sections with height to width ratios more than 4:1 tend to bend, rotate and topple (deep beam criteria in ACI Code 318)



# Geometry and Support Conditions - Spillways



Glendo Dam Chute Walls



Stampede Dam Inlet  
Control Structure



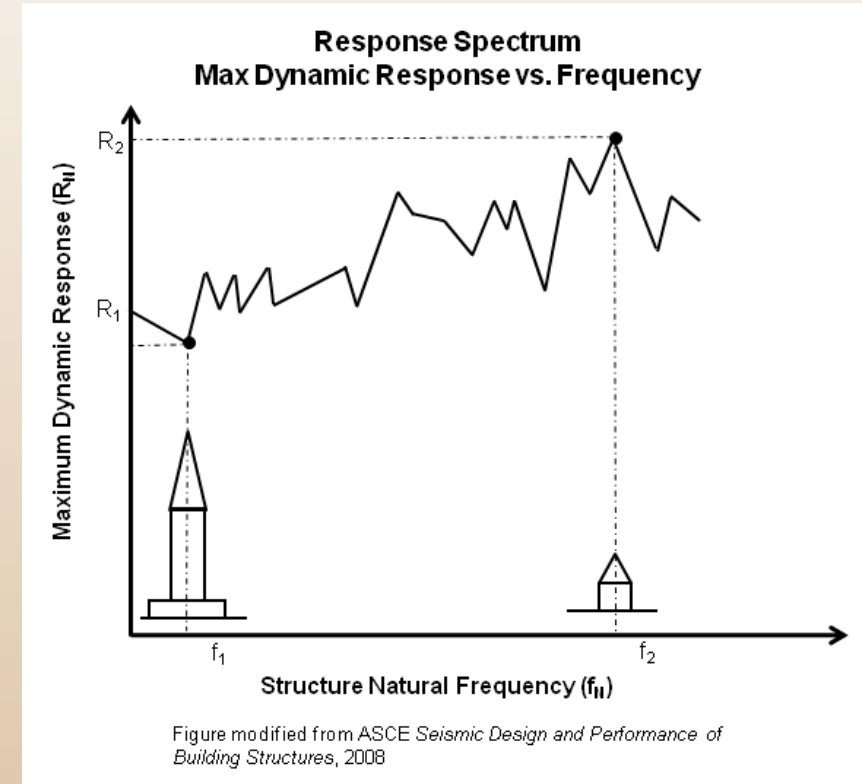
Stampede Dam Stilling Basin

- Examples typically not considered a reinforced concrete PFM
- Generally only consider gated spillway crest structure
- However failure could contribute to another PFM such as internal erosion through a gap that initiates between a spillway crest structure wall and the adjacent embankment



# Geometry and Support Conditions

- Structures have definite, signature dynamic characteristics
- The geometry greatly affects the natural frequency of the reinforced concrete member
- The natural frequency of the member decreases as the height to width ratio increases.
- The natural frequency becomes smaller as a reinforced concrete structure is damaged due to earthquake shaking



# Geometry and Support Conditions

## NATURAL FREQUENCIES OF VARIOUS SYSTEMS GRAVITY WALLS [R1]

### GRAVITY WALLS [R1]

$$H := 30 \text{ ft}$$

$$S := 0.7$$

$$B := H \cdot S$$

$$F := 0.000425 \frac{\text{sec}}{\text{ft}}$$

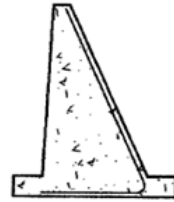
$$T := \frac{F \cdot H^2}{B}$$

$$f := \frac{1}{T}$$

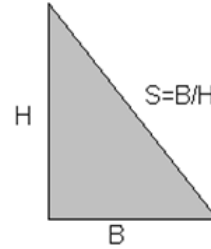
$$B = 21 \text{ ft}$$

$$T = 0 \text{ s}$$

$$f = 54.9 \text{ Hz}$$



REINFORCED CONCRETE  
RIGID-GRAVITY WALL



### CANTILEVER WALL FIXED AT BASE (B/H < 0.5) [R1]

$$H := 276 \text{ ft}$$

$$B := 8.33 \text{ ft}$$

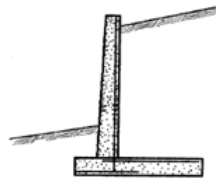
$$F := 0.000643 \frac{\text{sec}}{\text{ft}}$$

$$T := \frac{F \cdot H^2}{B}$$

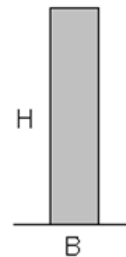
$$f := \frac{1}{T}$$

$$T = 5.8$$

$$f = 0.1$$



REINFORCED CONCRETE CANTILEVER  
SEMI-GRAVITY WALL



- Structural response to seismic loading will be different for sections:
  - ✓ on rock foundations compared to soil foundations
  - ✓ founded on the top of a dam where ground motions are generally amplified

# Reinforcement Material Properties

- Material properties of reinforcement directly contribute to strength of the concrete section. While the modulus of elasticity of steel is fairly consistent at 29,000 ksi, yield strength of reinforcement depends:

Steel Grade	Min. Yield	Ultimate	Years	
			From	To
33	33,000	55,000	1911	1966
40	40,000	70,000	1911	present
50	50,000	80,000	1911	present
60	60,000	90,000	1959	present
70	70,000	80,000	1959	present
75 <sup>1</sup>	75,000	100,000	1959	present

<sup>1</sup>Excludes the years from 1966 through 1987

- Historical reinforcement availability and yield properties can be found in CRSI Engineering Data Report No. 48 and ASCE 41 Seismic Rehabilitation of Existing Buildings.
- The shear strength of the reinforcement is typically taken as the yield strength.
- FEMA 356, *Pre-standard and Commentary for the Seismic Rehabilitation of Buildings*, recommends increasing these specified minimums by 125 percent for dynamic analysis





# Concrete Material Properties

- Key contributors to member strength and structural response
- Required concrete properties to estimate reinforced concrete member strength and structural response include:
  - Density
  - Modulus of elasticity
  - Compressive strength
  - Tensile strength
  - Shear strength
- Standard or assumed values for concrete material properties can be used in preliminary structural evaluations (Reference ASCE 41)
  - Uncertainty
  - Unconservative results
  - Concrete coring and lab testing may be required
  - See table of “Compressive Strengths for Concrete from Different Time Frames” in Chapter E-2 “Concrete Properties Considerations”



# Concrete Material Properties

## ➤ Construction joints

- ✓ Unbonded -> No tensile strength/reduced shear resistance
- ✓ Often adversely located in structure



Construction joint at  
geometric  
discontinuity

# Reinforcement Details

## ➤ Ductile vs. brittle failures

- Ductile failure much better than brittle failures
- Ductile failures occur much slower than brittle failures
- Ductile failures provide evidence of structural distress prior to failure
- Ductile failures allows time for repair or evacuation prior to failure
- Shear failures tend to be more sudden (brittle) than ductile type bending or tensile failures

## ➤ Ductile sections

- Require reinforcement design details per ACI code
- Detailing examples
  - stirrups confine areas of damaged concrete/help maintain post-seismic structural integrity
  - $A_{s(min)} = 200b_w d/f_y$
  - Shear strength based exclusively on  $V_c$  is okay provided  $A_s \geq A_{s(min)}$  and  $\rho \leq 0.75\rho_b$
- If a section does not meet the requirements above it doesn't mean it will fail or necessarily fail in a brittle manner.





# Reinforcement Details

- Older hydraulic structures were not designed for current seismic loads
- Seismic detailing requirements have changed dramatically over the last several decades
- Insufficient embedment lengths, splice lengths or hook details can result in sudden pullout failures
- Massive hydraulic structures are typically lightly or under-reinforced and can be greatly overstressed by large earthquakes and can yield and deflect excessively
- Older concrete structures are also typically more massive and the concrete strength and mass may compensate for the lack of reinforcement detailing.



# Structural System Considerations

- Structural systems that perform well during earthquakes
  - ✓ Dissipate energy through inelastic deformation
  - ✓ Alter dynamic properties (period shift)
  - ✓ Mobilize additional strength elsewhere in the system (highly redundant)
- Hydraulic structures are generally not highly redundant
- However, retaining walls have historically performed very well during earthquakes
- Seismic loads extend beyond performance database



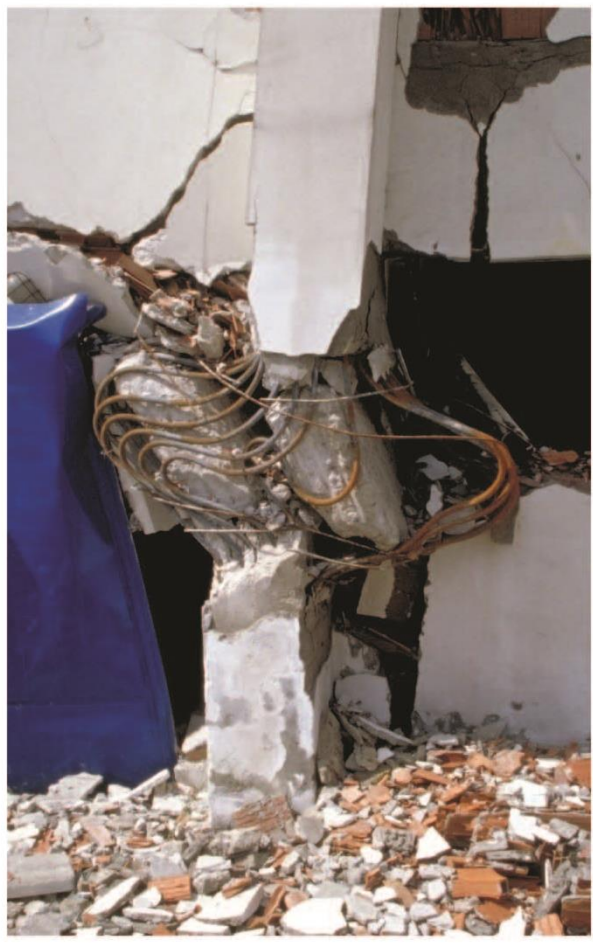
# Analysis Results Considerations

- When evaluating D/C ratios, it is important to evaluate values representative of the structure as a whole and not just localized maxima
- A progressive failure may occur if a localized area is overstressed, but this will take time under multiple earthquake peaks if there is potential for load redistribution
- Displacement criteria should be used to evaluate inelastic behavior of reinforced concrete members
- Biggest challenge for RA team
  - ✓ Severe damage may result from many cycles of demand exceeding capacity
  - ✓ The remaining strength of the damaged section is primarily a judgment call of the RA team





# Reinforcement Details Matter!



1999 Kocaeli, Turkey  
Earthquake



Shi-Kang Dam - 1999 Chi-Chi, Taiwan  
Earthquake – immediate aftermath

# Type and Duration of Load

## Static loads

- Examples - hydrostatic or soil pressures
- Typically act for long durations - sustained loads
- There may be no mechanism to stop or resist a section in the process of failing if the static loads exceed the capacity of the structure
- If a reinforced concrete structure is stable, the static loads *generally* have to change in some way to lead to failure
- Exceptions to latter point are in cases of advanced corrosion of reinforcement resulting in yielding and Alkali-Aggregate Reactions (AAR) leading to abnormal expansion and cracking of concrete in service.



# Type and Duration of Load

## Dynamic loads - Earthquake and Barge Impact

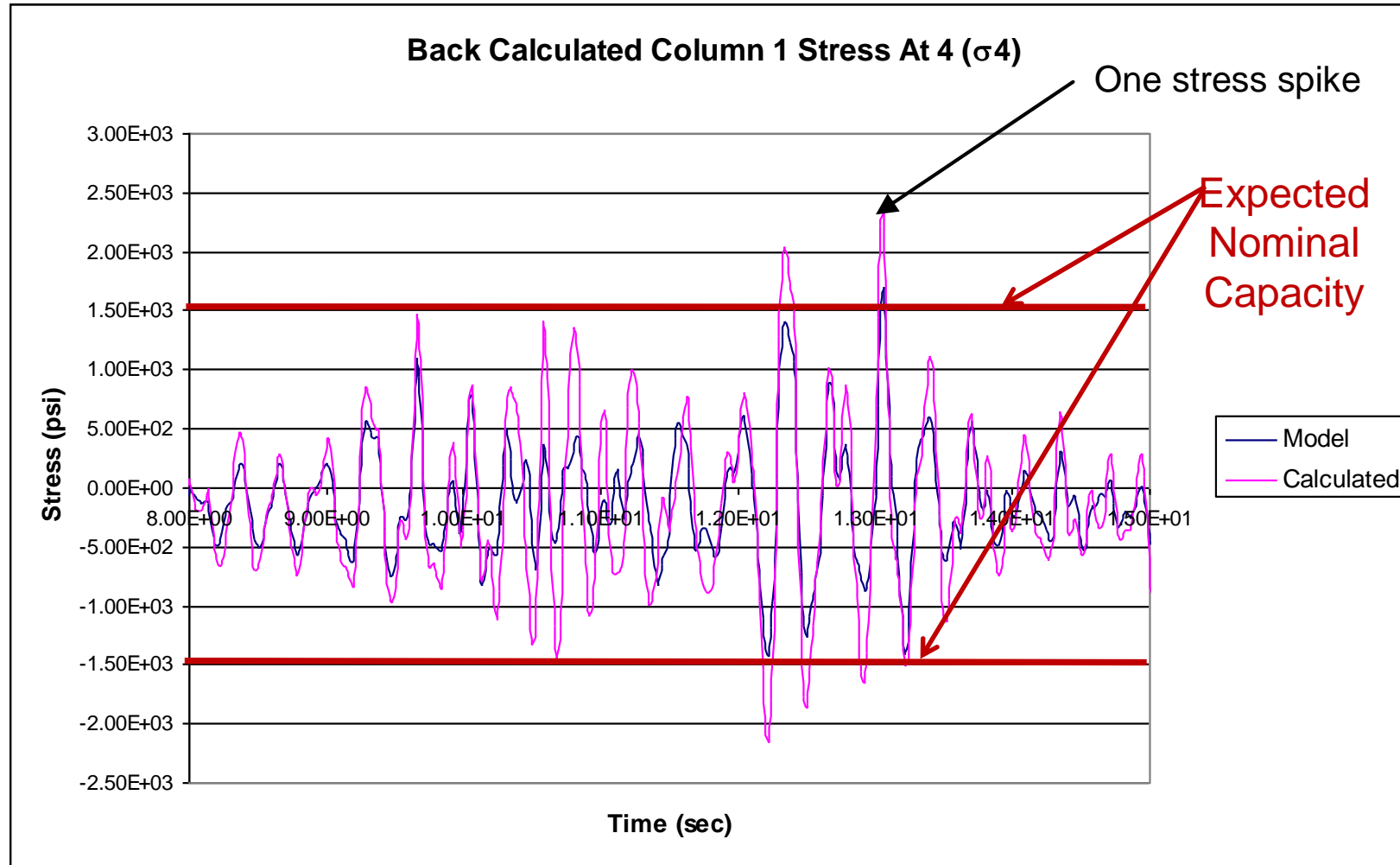
- Earthquake loads are cyclical and change direction rapidly
  - Barge Impacts are rapid and typically involve a large magnitude, highly concentrated first blow, followed by multiple smaller impacts as the barge moves along the face of the lock wall.
  - Sections may not crack through the member thickness even though the tensile capacity is exceeded for short durations
  - Dynamic loads of either type may not have sufficient duration or have enough significant stress peaks to completely strain a section to failure
  - As the member cracks and changes frequency, the response of the structure may change the loads and failure potential
- Post-seismic or post barge impact stability must consider the ability of a damaged section to carry static loads





# Type and Load Duration – Seismic

## Comparing Results from Dynamic FEM and “Traditional” Time History Analysis

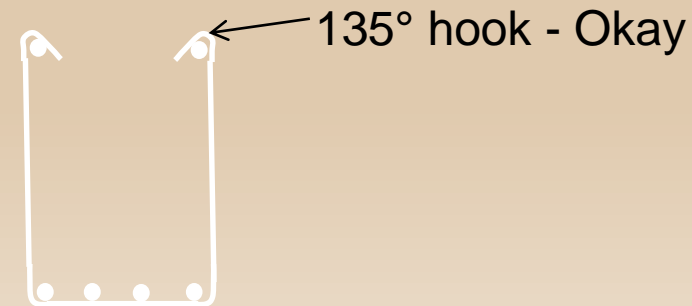
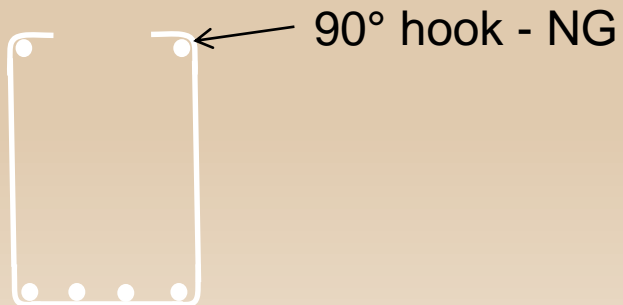


See the chapter on Concrete Properties Considerations.

It discusses this concept in more detail and provides performance curves to be considered for seismic loading and linear elastic analyses.

# Code Considerations

- Caution should be exercised when using National codes like ACI or AASHTO to compute the capacity of reinforced concrete sections.
- If a concrete structure does not meet current code requirements it does not mean the probability of failure is high.
- The sections tend to be pretty massive in concrete dams and the concrete and mass contribute to stability. The seismic hazard also could be low.
- Most codes are for new designs and assume ductile sections with adequate reinforcement details (adequate lap splices; appropriate confining reinforcement – closed ties or stirrups; and proper anchorage of ties and hooks – 135° seismic hooks)
- Consider looking at one of these references for assistance when evaluating an existing structures
  - ASCE 31 – Seismic Evaluations of Existing Buildings
  - FEMA 356, Pre-standard and Commentary for the Seismic Rehabilitation of Buildings



# Code Considerations

- Load factors and strength reduction ( $\phi$ ) factors
  - ✓ Used for new designs to
    - Address analysis and design uncertainties and assumptions (LF)
    - Account for variations in materials ( $\phi$ )
    - Account for variations in construction ( $\phi$ )
    - Generally build-in factors of safety
  - ✓ Do not apply for risk analyses of existing reinforced concrete structures
    - Compute the demand or load on the section without load factors
    - Compute the “true” or “expected” capacity of the section without  $\phi$
- During the risk analyses team members should consider:
  - ✓ The condition of the concrete and reinforcement
  - ✓ Severity of the environment
  - ✓ Deterioration due to alkali-aggregate reaction
  - ✓ Evidence of freeze-thaw deterioration
  - ✓ Evidence of corrosion





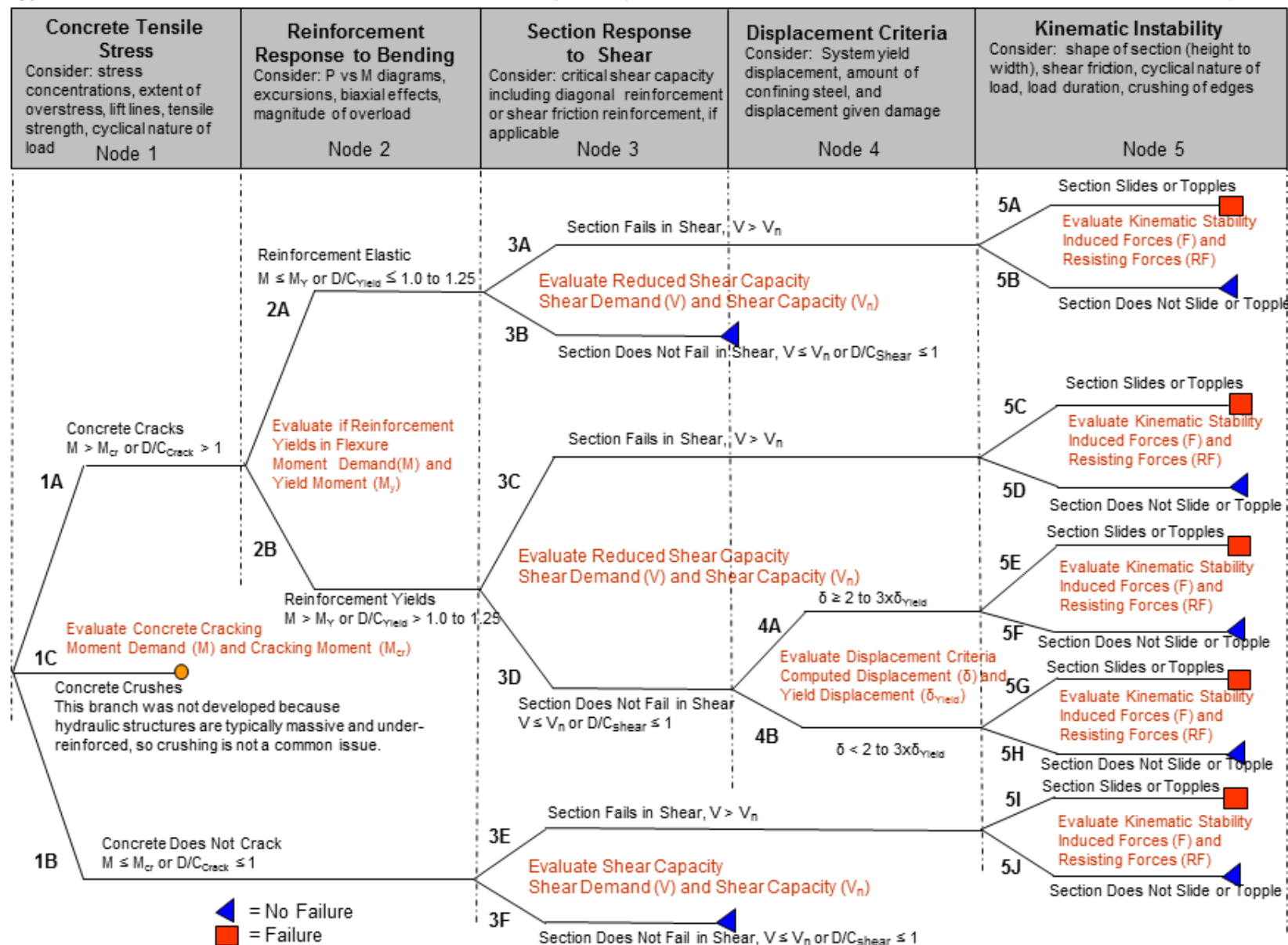


Figure 10-9 – Example Event Tree for Failure of a Reinforced Concrete Member

# Event 1 – Concrete Stress

Cracking moment criteria - compare moment demand ( $M$ ) to cracking moment capacity ( $M_{CR}$ )

$$\checkmark M \leq M_{cr}$$

where:

$$M_{cr} = f_t I_g / y_t \text{ (modified ACI Eq. 9-9)}$$

$f_t$  = concrete tensile strength per Chapter 20

$I_g$  = moment of inertia of the gross concrete section

$y_t$  = distance from the section centroid to the extreme tension fiber

- ✓ Tensile stresses from axial loads compared to  $f_t$
- ✓ Concrete crushing due to compressive stresses is unusual



# Event 2 – Reinforcement Response to Bending

Yield moment criteria - compare moment demand ( $M$ ) to yield moment capacity ( $M_y$ )

$$\checkmark M \leq M_y$$

$$\checkmark M_n \leq M_y \leq M_{pr}$$

where:

$M_y$  = section yield moment

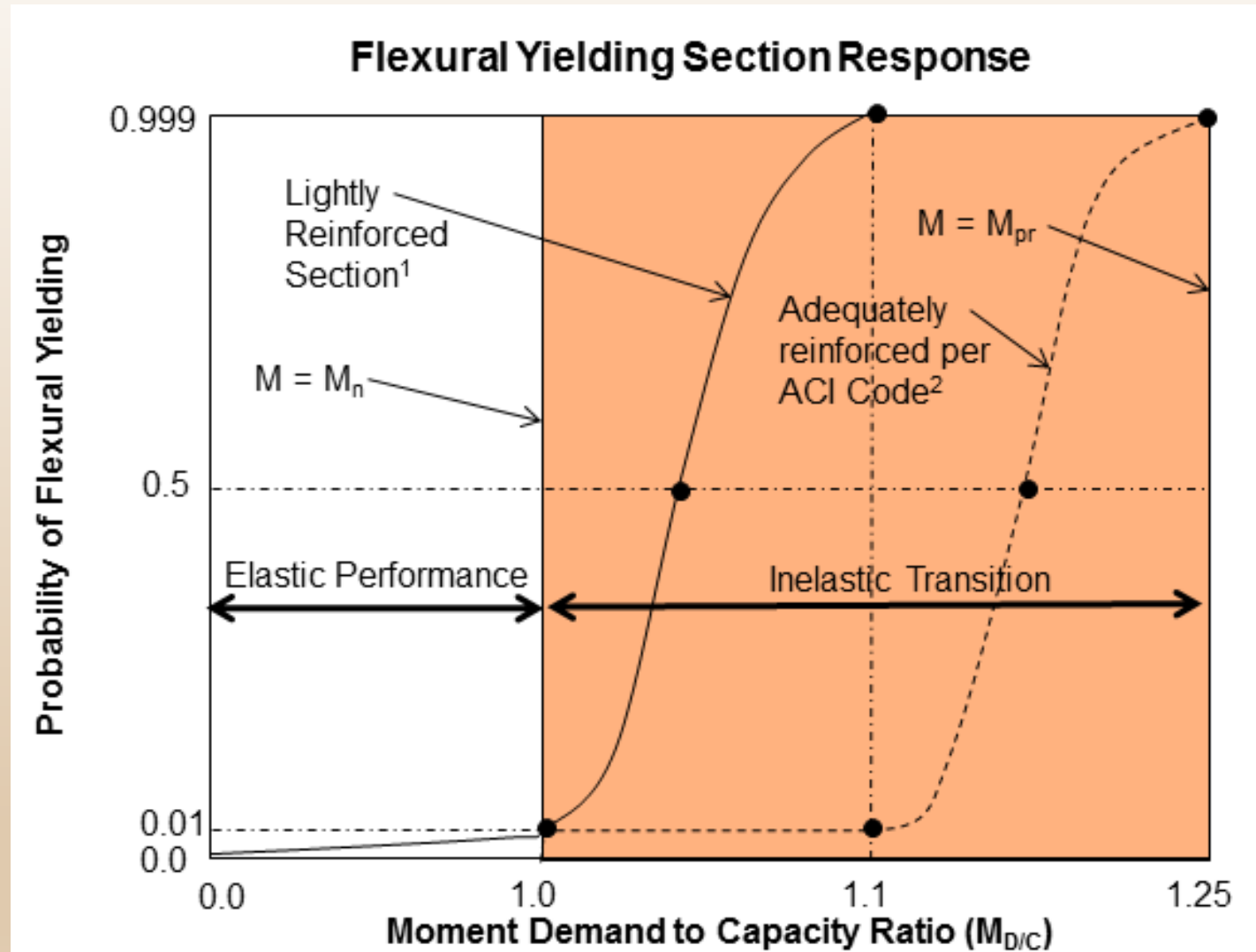
$M_n = A_s f_y (d - a/2)$  = nominal moment capacity

$M_{pr} = A_s (1.25 f_y) (d - a/2)$  = probable moment strength at plastic hinging

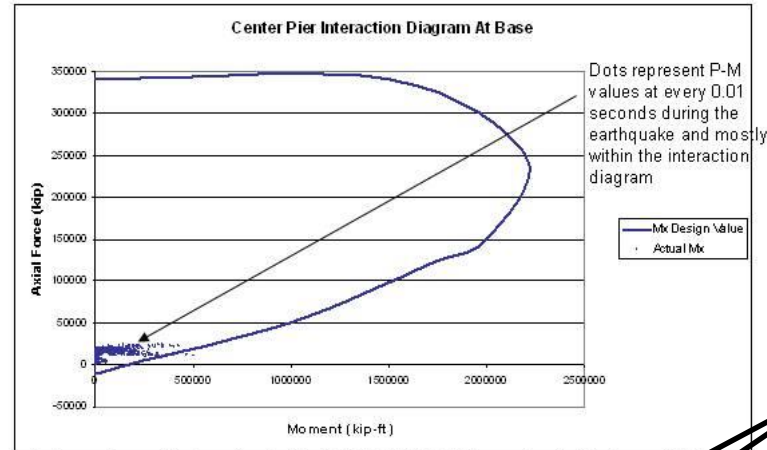




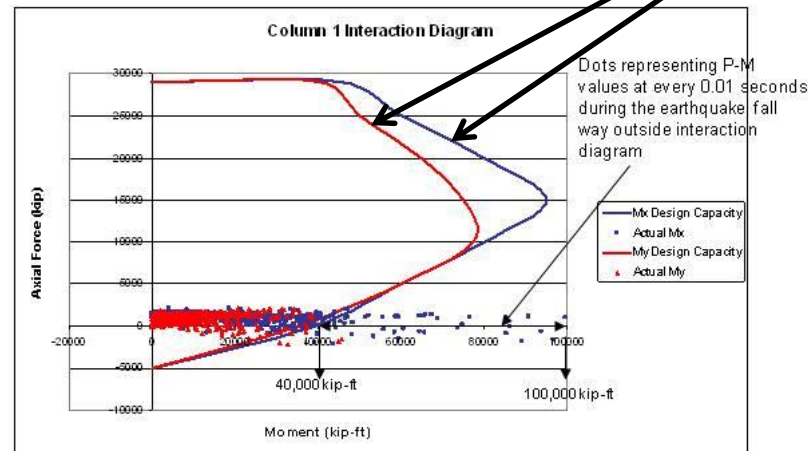
# Event 2 – Reinforcement Response to Bending



# Event 2 – Reinforcement Response to Bending



Maximum Demand to Capacity ratio is 1.25 (500,000 / 400,000) meaning steel is stressed 1.25 times beyond its yield

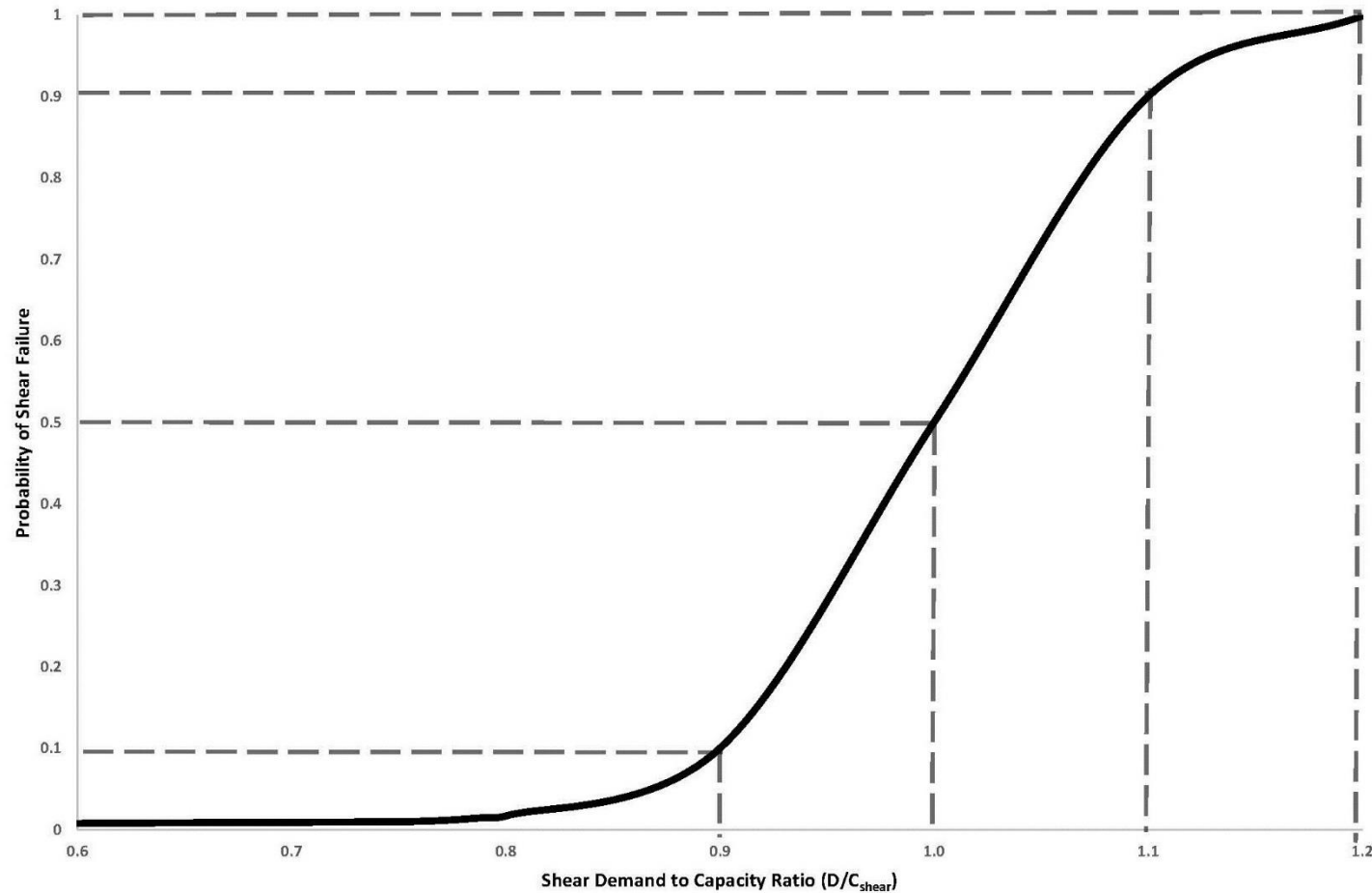


Maximum Demand to Capacity ratio is 2.5 (100,000 / 40,000) meaning steel is stressed 2.5 times beyond its yield

spColumn –  
interaction  
diagrams for  
member subjected  
to both axial load  
and flexure

# Event 3 - Section Response to Shear

Shear Fragility Curve  
(Moment Reinforcement Has or Has Not Yielded)



Response curve more representative of lightly or unreinforced sections - shear reinforcement will add ductility

For slender members ( $>4H:1W$ )

$$V_n = V_c + V_s$$

- $V_c$  = concrete shear strength
- $V_s$  = reinforcement shear strength

Shear friction reinforcement

- Need to consider type of shear failure when evaluating shear capacity – diagonal crack or horizontal crack
- Should be supplemental to primary flexural reinforcement



# Event 3 - Section Response to Shear

## ➤ Sliding

$$SF = (N - U)\mu + CA$$

where:

SF = Shear resistance

N = Normal force on the sliding plane

U = Uplift forces along sliding plane

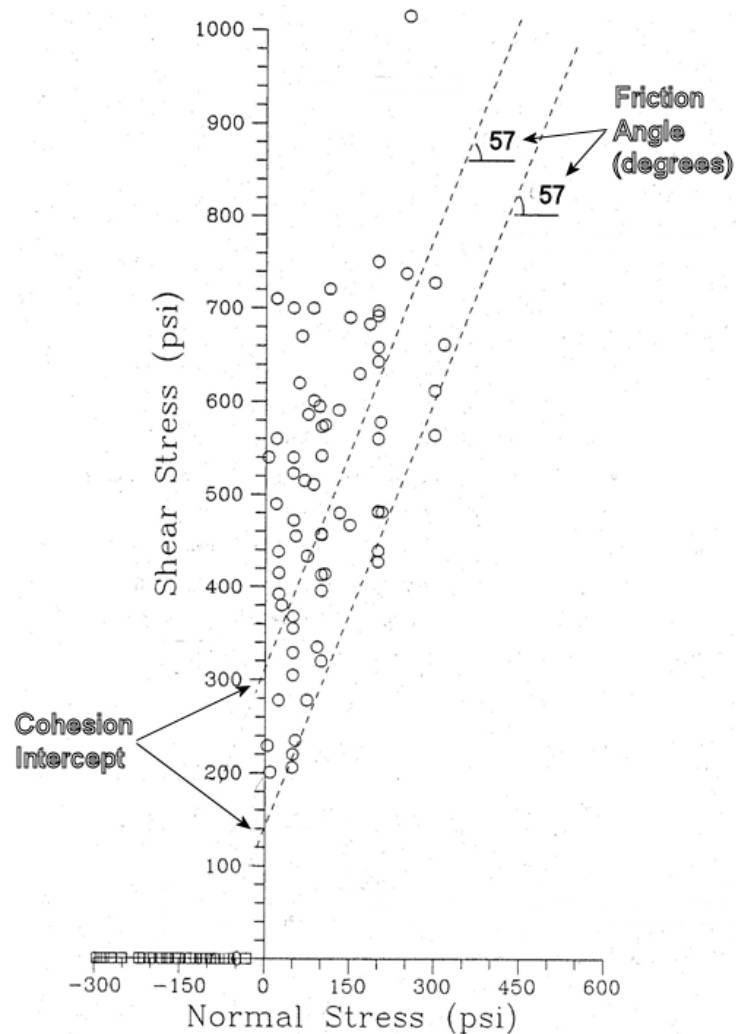
$\mu$  = Friction coefficient (tangent of the friction angle)

C = Cohesion (or apparent cohesion)

A = Area of slide surface

# Event 3 - Section Response to Shear

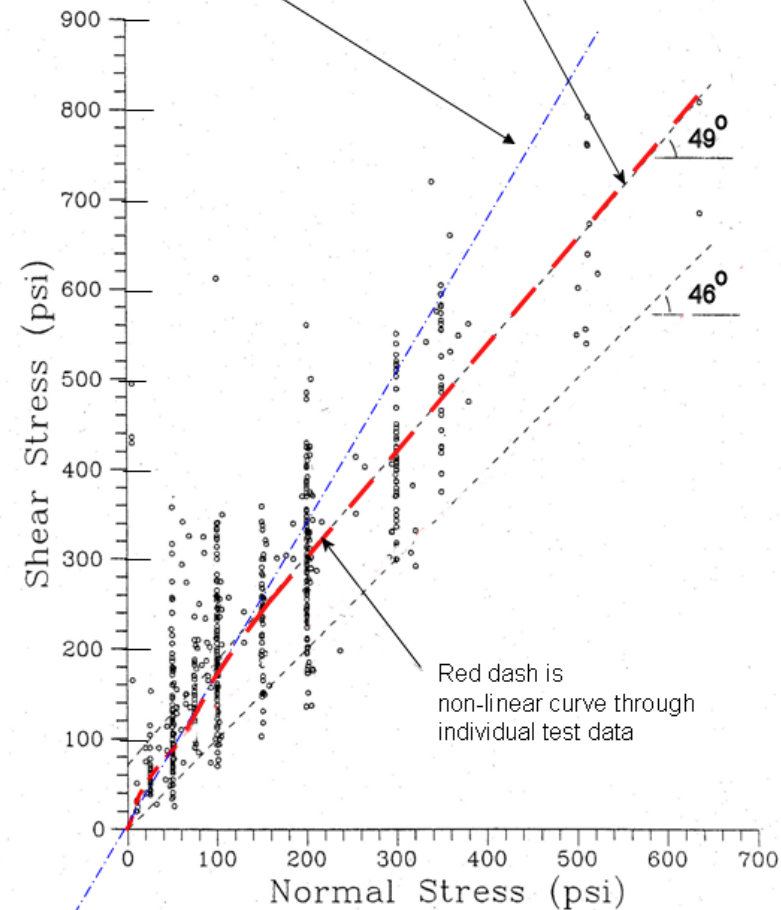
## Bonded Lift Line or Construction Joint



Peak Shear Strength of Concrete-Lift Joints

This straight line approximates non-linear curve at low normal stress  
 Apparent Cohesion = 0  
 Friction = 60 degrees

This straight line approximates non-linear curve at high normal stress  
 Apparent Cohesion = 70 lb/in<sup>2</sup>  
 Friction = 49 degrees



## Unbonded Lift Line or Construction Joint

Sliding Friction Shear Strength of Concrete-Lift Joints (Unbonded joints)

# Event 4 - Displacement Criteria

- Based on research at the University of Illinois at Champagne-Urbana by Mete Sozen
- Considers nonlinear behavior of section within structural system
- Determine nonlinear displacements in reinforced concrete system
- Structure may be viable if:  $\delta / \delta_{\text{yield}} \leq 2 \text{ to } 3$

# Event 4 - Displacement Criteria

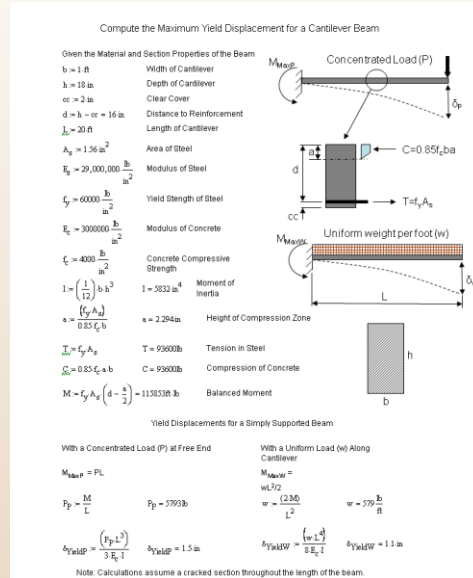
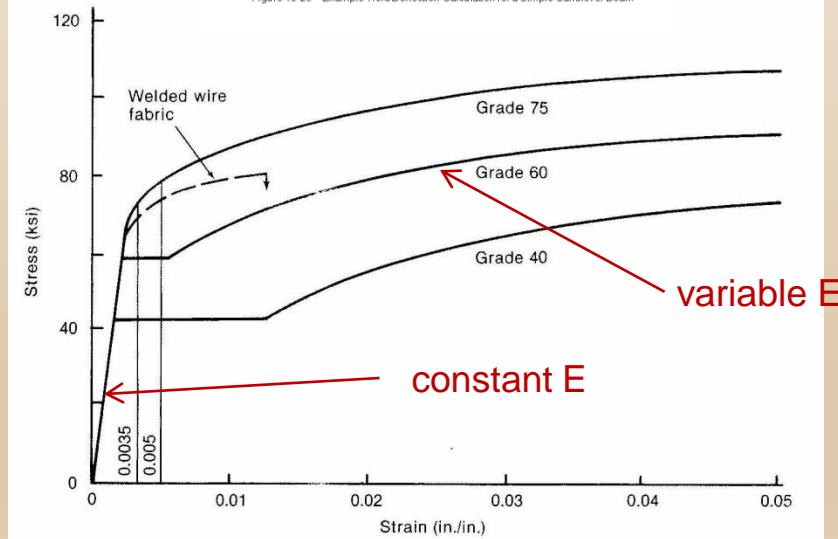


Figure 10-20 – Example Yield Deflection Calculation for a Simple Cantilever Beam



## ➤ $\delta_{yield}$ calculation

- ✓ Straightforward – constant E
- ✓ Actual yield deflections will likely be larger since moment of inertia will be that for a cracked section (method is conservative)

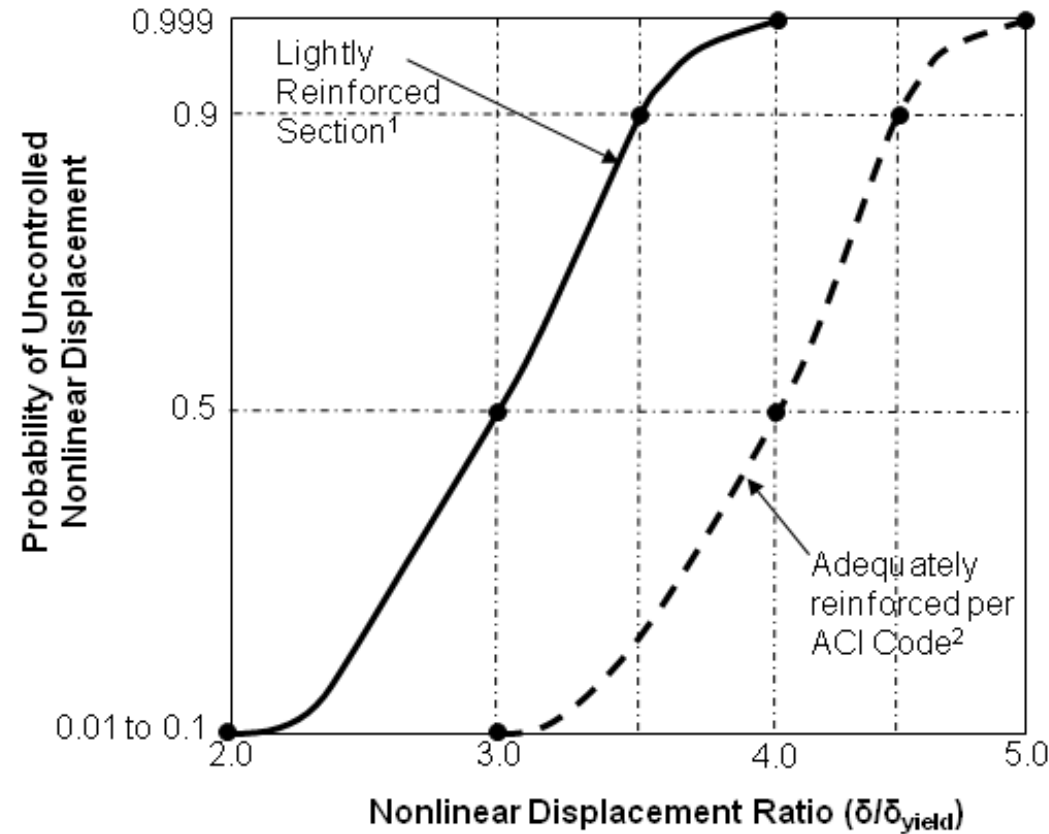
## ➤ $\delta$ calculation

- ✓ Not so easy – variable E
- ✓ Non-linear FEA most accurate approach
- ✓ Simplified approach use  $\frac{1}{3}$  to  $\frac{1}{2} E_c$
- ✓ System secondary (P- $\delta$ ) analysis



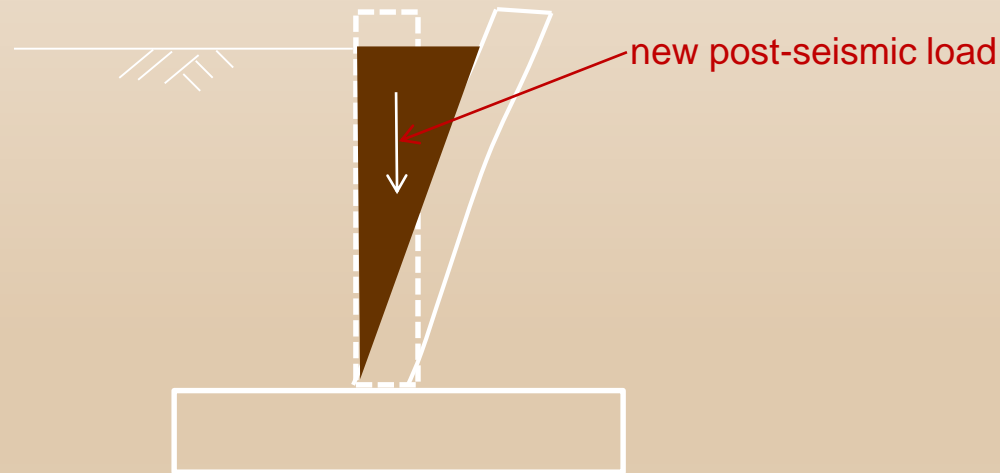
# Event 4 - Displacement Criteria

## Uncontrolled Nonlinear Displacement System Response (No Shear Failure)



# Event 5 - Kinematic Instability

- Three cases to consider
  - ✓ Independent concrete block separated from structure by shear failure (sliding)
  - ✓ Uncontrolled displacement of yielded member (toppling)
  - ✓ Post-seismic instability of yielded member



# Takeaway Points

- Failure mechanisms for various types of reinforced concrete structures are generally well understood, but there is significant uncertainty under seismic loading due to limited case histories.
- Many failures have been well documented on navigation structures, mostly resulting from barge impact.
- Virtually no failures of floodwalls or spillway walls have been documented that were the result of structural failures under expected design static or seismic loads.
- Concrete and reinforcement material properties are generally well understood but there may be limited information about in situ properties making risk analysis challenging.
- Type and Duration of Loading is important to understand – consider both static and dynamic (earthquake and barge impact) loading
- Consider both Ductile and Brittle Failure mechanisms
- Seismic reinforcement details have changed dramatically over the past few decades; older concrete hydraulic structures may be more susceptible to brittle failures under seismic loading, but most are pretty robust and probably are not more vulnerable in general
- Modern design codes should be used with care when computing capacity of older reinforced concrete structures

